Penning Fusion Experiment

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For over forty years, physicists have pursued the goal of a fusion energy device. Work toward this goal has concentrated on devices that attempt to heat and store neutral plasmas, such as gases consisting of positive ions and electrons in equal or almost equal numbers. These devices have reached impressive temperatures and densities, but the confinement times have left much to be desired because neutral plasmas are prone to instabilities.

At the other end of the spectrum are Penning and Paul traps, which store nonneutral plasmas consisting of pure clouds of electrons, positive ions, or negative ions. These devices have achieved virtually infinite confinement times, but the densities of the stored plasmas have been limited by the Coulomb repulsion between the constituent particles. The limiting value of the density attainable is known as the Brillouin limit. The Penning Fusion Experiment (PFX) seeks to circumvent this limitation in a small electron Penning trap.

In their simplest form, Penning traps are composed of a ring electrode and two end caps (Fig. II-29). If the ring electrode is biased positively with respect to the end caps, the potential inside the trap is a saddle potential that provides confinement for electrons along the trap axis. Obviously, the electrons are not confined radially by the electrostatic potential; they are instead prevented from escaping radially by a magnetic field that is applied parallel to the trap axis. An electron confined by these fields will execute an axial oscillation in the electrostatic well and a cyclotron orbit about the magnetic-field lines. Additionally, the electric and magnetic fields will give rise to an $E \times B$ drift of the center of the cyclotron orbit about the trap axis.

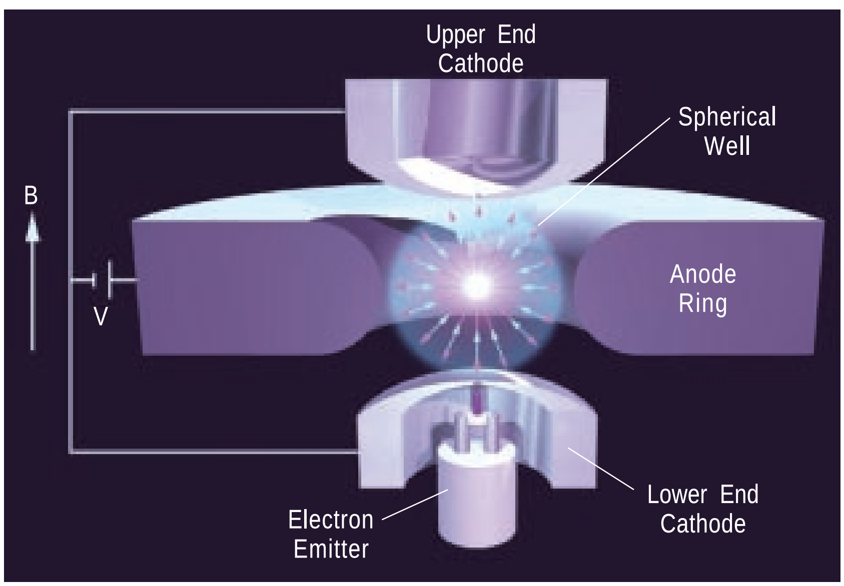


Fig. II-29. Schematic representation of the Penning trap showing the effective spherical well boundary and the reflected electron trajectories.

PFX uses these oscillations to produce a high-density plasma at the center of the trap. This is accomplished by introducing a low-energy, low-divergence electron beam from a LaB_6-crystal electron emitter through a 400-μm-diameter hole in the lower end cap and reflecting it by means of a small, negative voltage applied to the upper end cap. In the absence of scattering, an electron in the beam will simply return to the emitter or to the lower end cap and be lost from the trap. If, however, some of the electron's energy is scattered from its axial motion into its radial degrees of freedom, the electron will remain confined in the axial well and will execute a combination of the oscillations described above.

For a proper choice of trapping potential and applied magnetic field, the period of an electron's axial motion will be twice the period of its radial motion, and any orbit originating at the center of the trap will be constrained to pass through the center again. A collection of electrons that all follow such orbits will produce a dense, "focused" plasma. An alternate picture is that the combined electric and magnetic fields provide an effective well that is spherical for the proper choices of the field strengths. Then, any trajectory originating at the trap center will be reflected back on itself by the spherical wall of the well. This situation is shown schematically in Fig. II-29.

It is important to note that the electrons executing these orbits have zero (or near-zero) angular momentum. To preserve this beam-like state, it is essential that scattering occur mostly at or near the trap center. Excessive numbers of collisions away from the center will result in a more-or-less uniform electron cloud that will effectively wash out the focus. To minimize this thermalizing scatter, we operate PFX at liquid-helium temperature, thereby assuring an extremely low background pressure ($<10^{-10}$ torr). Intrabeam scattering does occur throughout the electron-beam volume but, because of the narrow energy distribution of the beam electrons, proceeds at a sufficiently slow pace to allow focusing effects to dominate the thermal background that is generated. In fact, as we explain later, a small amount of intrabeam scattering is desirable.

In order to maximize the density attained, it is desirable to use high electric-field strengths. Hence, the trap must be designed to hold high ring voltages. The present trap, through judicious choice of materials and the excellent vacuum achieved in the cryogenic environment, is capable of holding up to 30 kV across the 1.5-mm gap between the ring and the end caps. Addition of the magnetic field significantly degrades the voltage standoff so that the actual operation is limited to voltages below 10 kV. Figure II-30 is a picture of the trap assembly, which consists of titanium electrodes and precision ceramic spacers.

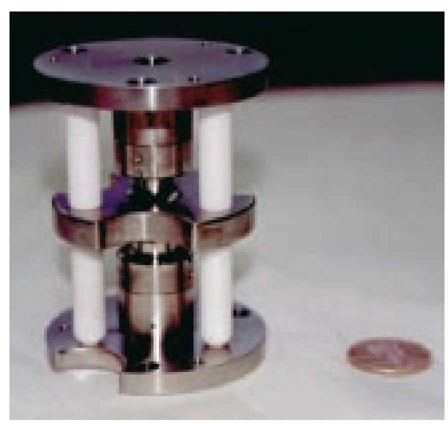
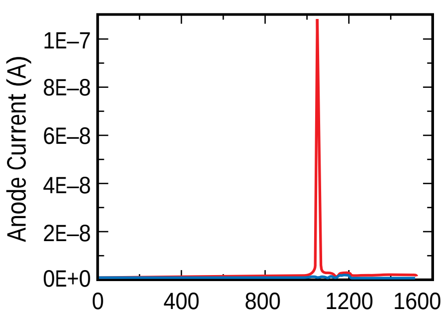


Fig. II-30. The trap used in these experiments. The spacing between the titanium end-cap electrodes is 6 mm and is maintained to within 5 μm by high-precision, polished alumina spacers. The inner diameter of the ring electrode is also 6 mm.

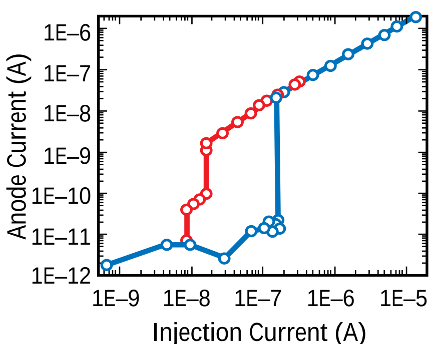
PFX has been operating for almost two years and has conclusively demonstrated the formation of a density focus. The hallmark of this focus is scattering of the injected electron current to the ring electrode. As is evident from Fig. II-29, the electron orbits in the focused, spherical state extend all the way to the ring and thus allow electron current to flow from the beam to the ring. Figure II-31a shows a plot of the current flowing to the ring for a fixed magnetic field as the ring voltage is increased. The sharp peak occurs at the voltage at which a focused state is expected to exist for the given magnetic field.

Current to the anode is shown for two different values of the electron current that is injected through the hole in the lower end cap. For the lower injection current, essentially no current flows to the anode, while at the higher current, a full 20% of the injected current is deflected to the ring. An interesting indication of the mechanism by which the focus establishes itself appears when one examines more closely the relation between the injected current and that current flowing to the anode ring. This data is shown in Fig. II-31b for a fixed magnetic field and anode voltage. The blue curve is for increasing injection current, while the red curve is for decreasing injection current.

The hysteresis is an indication of the role played by thermal electrons. These electrons are scattered out of the injected beam by the intrabeam scattering mentioned earlier and form a uniform (that is, unfocused) thermal population that coalesces to the trap center and remains there for several seconds. An equilibrium is established between scattering into and loss out of the trap, so the density of this population is related to the magnitude of the injected current. At some threshold value, the space charge of the thermal plasma becomes large enough to significantly deflect the injected electrons, thereby forming a density focus as described above. Once established, the focus maintains itself by virtue of its own space charge disintegrating only when the replenishment rate falls below a critical value. This critical value is represented by the lower threshold of the red curve.



(a)



(b)

Fig. II-31. (a) The total electron current flowing to the anode ring plotted as a function of the voltage for a fixed magnetic field with two different values of the current injected into the trap. (b) The total electron current flowing to the anode at a fixed "spherical" point as a function of the total current injected into the trap.

Although the attained density has not been directly measured, a numerical calculation of the density has been performed based on PFX data and physical parameters. The results of these calculations are shown in Fig. II-32. The calculation shows a plasma core of peak density approximately 35 times the Brillouin limit with a radius of roughly 20 μm. This calculation is consistent with core sizes inferred from the widths of resonance peaks in various scattering diagnostics. Also shown in Fig. II-32 is the potential in the trap volume, including the space-charge potential of the electron plasma.

Figure II-32 provides the impetus for much of the future work planned for PFX. One can imagine introducing neutral atoms into the trap volume that will be ionized and accelerated by collisions with plasma electrons. The space charge of the electron plasma will confine some of the ions thus produced and will result, it is hoped, in a high-density, thermonuclear plasma. We are presently working on such a gas-introduction capability.

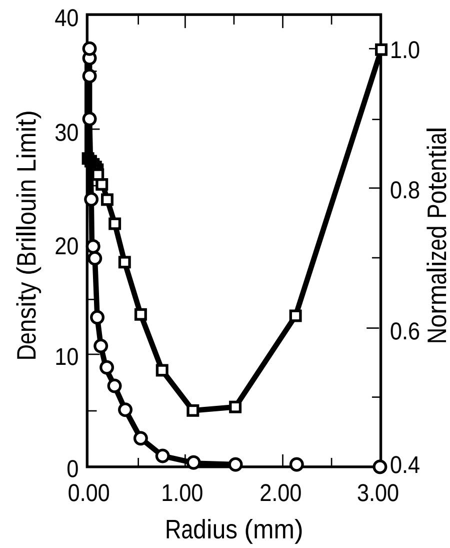


Fig. II-32. The calculated electron density in the trap volume (circles) plotted as a function of the radius, which is normalized to the Brillouin limit. Also shown is the sum of the vacuum potential and the electron plasma space charge (squares), which is normalized to the vacuum potential at the trap wall.